Establishing Trust in NASA's Artemis Campaign Computer-Human Interface (CHI) Implementation

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***Abstract*— The NASA Artemis campaign will return humans to the Moon. This time, with the help of commercial and international partners, the campaign's objective is a permanent Moon base. The Moon base infrastructure, including an orbiting station and surface assets, will be developed for astronauts to stay for the long haul to learn to live and work on another planet in preparation for an eventual Humans-to-Mars mission. As the roundtrip communication delays increase in deep space exploration, the crew will need more onboard systems autonomy and functionality to maintain and control the vehicle or habitat. These mission constraints will change the current Earth-based spacecraft to ground control support approach that will demand safer, more efficient, and more effective Computer-Human Interface (CHI) control. For Artemis, CHI is defined as the elements that the crew interfaces with: audio, imagery, lighting, displays, and crew controls subsystems. Understanding how CHI will need to evolve to support deep space missions will be critical for the Artemis campaign --especially crew controls, which is the focus of this paper. How does NASA ensure crew controls are reliable enough to control complex systems and prevent a catastrophic event due to human error--especially when the astronauts could be physiologically and/or psychologically impaired? NASA's approach to mitigating catastrophic hazards in human spaceflight system development such as crew controls, is through a holistic system engineering and Human System Integration (HSI) methodology. This approach focuses on incorporating NASA's Human-Rating Requirements to ensure consideration of human performance characteristics to control and safely recover the crew from hazardous situations. This paper discusses, at a high level, CHI for the Artemis campaign. Next, a discussion of what it means to human-rate a space system crew controls and how trust in CHI begins with the NASA human rating requirements. Finally, a discussion on how systems engineering and the HSI process ensure that crew control implementation incorporates the NASA human-rating requirements.**

Keywords—Artemis, systems engineering, human-rating, human systems integration, computer-human interface, human error

I. INTRODUCTION

The NASA Artemis program will return humans to the Moon. This time, with the help of commercial and international partners, the program's objective is a permanent Moon base [1]. With the help of commercial and international partners, the Moon base infrastructure, including an orbiting station and surface assets, will be developed for astronauts to stay for the long haul to learn to live and work on another planet in preparation for an eventual Humans-to-Mars mission. Two key Artemis Campaign objectives will be:

- Demonstrate new technologies, capabilities, and business approaches needed for future exploration, including Mars.
- Study the Moon to learn more about the origin and history of Earth, the Moon, and our solar system.

As the roundtrip space communication delays increase, the crew will demand more onboard systems autonomy and functionality to maintain and control the vehicle or habitat. These mission constraints will change the current Earth-based spacecraft to ground control support approach that will demand safer, more efficient, and more effective Computer-Human Interface (CHI) control. For Artemis, CHI is defined as the elements that the crew utilizes to accomplish the mission that interfaces with the electronic systems on the vehicle: audio, video, lighting, displays, and crew controls. Understanding how CHI will need to evolve to support deep space missions will be critical for the Artemis campaign, especially crew control systems, which is the focus of this paper. The CHI elements, especially the human control systems, must be developed for human-rating certification. Human rating subjects the system development to more scrutiny to establish trust in the crew controls by considering human capabilities, controlling known hazards with suitable certainty to be considered safe for human operations, and ensuring safety risks are evaluated throughout the lifecycle and deemed acceptable for human spaceflight.

For human interfaces, trust can be defined loosely as the human, the machine, and the interactions and interdependencies between them that establish confidence in system status data provided to the user and the execution of commands reliably and confidently. It's not just that the system will operate correctly but also from a psychological standpoint, it gives the crew a feeling of confidence and security that the behavior of the system is understood and will perform as verified/validated throughout the mission [2]. This

is important especially as the missions extend beyond the Moon and risks/hazards can affect the mental state of the crew. Critical to the development of trusted crew controls is a systematic development approach that starts with human rating based on three principles:

Principle: The human rating process ensures that designing, evaluating, and assuring the total system can safely execute the required mission.

Principle 2: Design features and capabilities that accommodate human interaction with the system that enhances overall safety and mission success.

Principle 3: The system has design features and capabilities to enable the safe recovery of the crew from hazardous situations.

Though the human rating process relates to the entire spacecraft or space element (such as a habitat, rover, or space suit), this paper covers only the part of human rating the crew controls that contribute to the overall human rating of the spacecraft or space element containing a crew control subsystem.

This paper discusses, at a high level, CHI for the Artemis campaign. Next, a discussion of what it means to human-rate space system crew controls and how trust in the CHI begins with the NASA human rating requirements. Finally, establishing trust in the crew controls is done via systems engineering and the human system integration (HSI) process that ensures crew control implementation incorporates the NASA human-rating requirements.

II. Artemis Computer-Human Interface (CHI) Elements

Figure 1 shows the various Moon elements that will contain crew control systems and the related documents discussed later in the paper. Artemis comprises several elements beginning with the Orion Spacecraft that transports astronauts from/to Earth to/from the Moon.

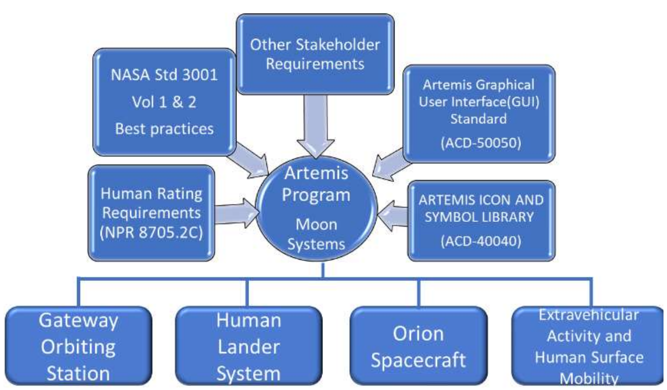

Fig. 1. Human Requirements Flow Down to Artemis Elements (Credit: Author)

The Gateway provides a permanent orbiting space station around the Moon. The human lander system (HLS) provides the astronauts with the means to transport them from Orion or Gateway to the Moon and back to the Orion spacecraft or Gateway. The Extra-Vehicle Activity (EVA) suit is used to explore the lunar surface and perform EVA activities for maintenance on Gateway. Finally, there are the surface assets, such as the logistics modules used to deliver cargo to the Moon's surface and experiments conducted on the Moon. Each of these Artemis elements contains CHI elements. A short description of the CHI elements as they apply to the Artemis systems follows.

A. CHI Element Description

Audio - The audio system typically includes wireless and wired noise-canceling headsets (microphone + ear pieces) and a headset interface unit to control speaking modes such as push-to-talk and volume control. Panel-mounted speakers are also used for hearing a conversation when headsets are not needed and the acoustics are acceptable for hearing a conversation. Also, there are handheld microphones too that can be used. Figure 2 shows a Space Station workstation that contains an interface for audio devices such as a handheld microphone to permit astronauts to communicate with the ground or other station modules. Audio components like those mentioned will provide voice communications between the various endpoints, such as Orion and Gateway, inside the Gateway between modules, Orion or Gateway with the HLS, HLS or Gateway with extra vehicle activity (EVA), or any ground stations. The audio communications also include communications between EVAs. A key performance metric of the audio system is the intelligibility of audio in the various acoustic environments of the spacecraft, EVA suits, or habitats.

Fig. 2. Astronaut Karen Nyberg speaks into a handheld microphone on space station while conducting a session with the Advanced Colloids Experiment (Photo Credit: NASA)

Imagery - Imagery systems provide viewing and recording of various Artemis events such as the launch of the Space Launch System (SLS) booster and core stage separation. For Orion, imagery use includes external views of the vehicle, in-cabin observations and video conferencing with the ground, and vehicle inspection. Video cameras such as shown in Figure 3, a

space station-enhanced high-definition camera with a luminaire, will provide imagery to Earth and situational awareness to the crew when performing rendezvous operations, EVAs, or surface operations. The HLS will contain cameras for an external view of the lander and various interior views. The EVA suits and Moon rovers will also have cameras for streaming back imagery from their exploration location on the Moon or doing EVAs on Gateway. Each motion or still imagery camera will be controlled either remotely by the crew (gloved or ungloved) or by mission control commands.

Fig. 3. Enhanced HD video camera externally attached to the International Space Station (Photo Credit: NASA)

Lighting - Lighting provides the illumination required to aid the crew to perform mission tasks that include taking video and still images--especially in situations where a critical task is performed. On-orbit, lighting will be used for EVA and robotic operations, docking between spacecraft, and interior spacecraft visibility. Internal lighting, such as seen in Figure 4, will provide lighting for the crew and maintain the crew's circadian rhythm. These lighting sources will use solid-state lighting devices that can be programmed to vary the lighting intensity and color spectrum. For surface operations, the HLS will be equipped with internal and external lighting to assist in tasks, including descent to the Moon's surface and scientific experiments near the HLS. For EVA, the suit will be equipped with lighting to help with the visibility of EVA tasks.

Fig.4. Space Station solid state lighting assembly that can be programmed to adjust lighting and color intensity (Photo credit: NASA)

Crew Controls- Figure 5 shows the Orion spacecraft cockpit as a representation of what crew controls will look like in the Artemis elements. For EVA suits, the crew controls will be much smaller as size and power are implementation constraints. Crew controls provide the crewmember the means to command and control a space system. The crew commanding mechanisms could be a combination of hand controllers, buttons/switches, levers, touch screens, or even voice or gesture. These devices can manually control specific functions, either benign or safety-critical, of the vehicle, rover, EVA suit, or other human-occupied space system components. As part of crew controls, feedback on the status of the crew control command execution is required.

The crew control design is critical to ensuring astronauts can easily use the interface to command and receive feedback from actions taken. Therefore, human systems integration which is explained later in the paper is important. The backup to crew controls is mission control which can also send commands when the astronauts cannot. However, as we go deeper into space and longer communication delays, the spacecrafts and habitats will have to depend more on onboard autonomy to help the astronaut operate the space system. Crew controls/human interface interaction design with autonomy will be important to ensure the crew can monitor the state of the autonomy and take over in case the autonomous system becomes corrupt. This will be an area to prove out in the Artemis Campaign.

Fig.5. Orion spacecraft glass cockpit (Photo credit: NASA)

Displays- Displays such as those shown in Figure 5 provide visual feedback to the astronaut of commands initiated/executed or vehicle system status. Depending on the Artemis vendor, the display could also provide the means for benign vehicle commanding, such as activating lighting via touchscreen technology. For EVAs, the current thinking is to give a heads-up display on the helmet for visual feedback on the EVA suit status.

Depending on the task, feedback to the user can be provided via display lights (such as LEDs), alphanumeric or graphical displays, and/or audio messages. For critical events, crew commanding must be examined from a safety-critical application. An incorrect command could result in a hazardous situation. The key to establishing trust in the safety of the crew controls lies in ensuring compliance with human rating requirements.

III. Crew Control Trust via the Human Rating Process

As mentioned, trust is loosely the user confidence in system status data and reliability and confidence in the execution of commands. This trust requires a holistic understanding of the human, the machine, and the interactions and interdependencies between them. Unlike robotic missions, human spaceflight missions take additional safety and design steps to ensure the space systems (such as the launcher, spacecraft, EVA suit, or subsystems) minimize risks to the crew. Human rating for the ground crew and the public is also addressed but under other NASA policies.

A. Human Rating Requirements Documents

Referring again to Fig. 1, the key documents that feed into the Artemis campaign help define requirements related to the human rating of space systems. The NASA Human Rating Requirements (NPR 8705.2C) document defines the requirements, processes, milestone reviews, and verification for human rating certification. Though the requirements are for a space system, many of the requirements flow down to the subsystem depending on the function the subsystem is to perform. As defined in NPR 8705.2c, a human-rated system accommodates human needs, effectively utilizes human capabilities, controls hazards, and manages safety risks associated with human spaceflight. It also provides, to the maximum extent practical, the capability to safely recover the crew from hazardous situations [3]. H.C. Shivers [4] gives a good summary of the requirements and processes for the human rating of a system.

The two documents, ACD-50050 and ACD-40040 define requirements that ensure all the Artemis elements have a common graphical user interface (GUI) and Icons/symbols, respectively. This establishes consistency across all displays in Artemis vehicles and elements. These documents help ensure usability and reduce crew workload by standardizing what the crew sees on the displays and the meaning across all elements they interact with on an Artemis mission. Thus, astronauts do not have to relearn new GUIs and icons/symbols when they transition from the Gateway to HLS, for example. At the time of this writing, the said documents are still in review for baselining.

The NASA-STD-3001 is a two-volume set that establishes standards for crew health (vol 1) and uniform technical requirements for the design, selection, and application of hardware, software, processes, procedures, practices, and methods for human-rated systems (vol 2) [5]. Volume 2 addresses the requirements for equipment and operational interfaces such as displays and controls for the flight crew. This document applies to Artemis systems required to obtain a human-rating certification as defined in NPR 8705.2C. Collectively, these documents, along with other stakeholder requirements, make up the system requirements document that helps establish trust by providing common requirements to build crew controls that factor into the performance of the human element and are safe and reliable to use in the mission. Not shown in Figure 1, but critical to successful design, is the systems engineering process that includes qualification testing of the crew control systems and the HSI process for integrating the human into the system. These will be discussed later in the paper.

IV. What is the human rating of a Space System?

What follows is a high-level discussion of establishing trust in the use of crew controls through the NASA spaceflight system human rating and certification process. Though human rating applies to the entire space system, this paper focuses on the crew controls of a space system that are critical to ensuring safe commanding during nominal and off-nominal/emergency conditions. Ultimately, for the system to meet human rating requirements, the human rating certification requires that all subsystem components also meet the human rating requirements.

A. Principles of Human Rating

A NASA key core value is that a successful mission begins with the safety of all personnel including the crew. The idea behind the human-rated system is that NASA understands the risk of human spaceflight and that a risk-free human spaceflight mission is impossible to attain. However, though all risks cannot be eliminated, they can be mitigated through a methodical engineering approach that leverages fundamental principles of human rating.

NPR 8705.2C defines three principles of human rating:

1) Assure the total system can safely conduct the mission,
2) Include human interaction design capabilities to enhance overall safety and mission success, and
3) Enable safe recovery from a hazardous situation.

Hardware meeting the environmental requirements is only part of the process toward human rating. The principles define and implement the additional processes, procedures, and requirements necessary to produce a human-rated system. Figure 6 shows a Venn diagram of the three key human rating principles to achieve human rating certification. Each of these principles contributes to the human rating of crew controls.

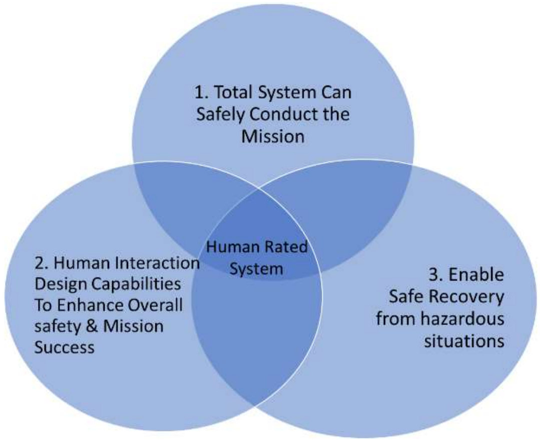

Fig. 6. Human Rating Principles (Diagram credit: Author)

The first principle is based on the reference mission that the space systems will be human-rated certified to. Each mission has its unique risks that the system must mitigate. Though human rating is written at the vehicle level, it also applies to crew controls. Within the crew control context, we must look at what tasks are needed to operate the vehicle through all mission phases and to ensure tasks are performed safely, such as manually landing the human lander on the Moon.

Some of the safety requirements that affect the crew control design include:

a. Loss of Crew (LOC)/Loss of Mission (LOM) reliability requirements must factor in the reliability of the crew controls to the probabilistic safety analysis. This not only requires a reliability analysis as part of the human rating, but also a comprehensive crew control qualification test program is in place.

b. Single failure tolerance to catastrophic hazards requires the crew control design to ensure that critical functions such as parachute deployment or fire suppression have an alternative control. Automation may be part of the design that relies on a part of the hardware to execute the critical command, but there should be an alternative command path to execute the same command.

c. There is a human rating requirement related to detecting and annunciating faults that affect critical systems, subsystems, or crew health. For crew control, this calls out ways to alert the crew (either visually, auditorily, or both) about faults that have been detected in critical systems such as life support.

The second principle addresses ensuring the crew control design not only provides a clear and concise way of commanding and controlling a system, but also prevents inadvertent activation of critical commands that could have catastrophic results. Examples of requirements related to this second principle include:

a. The crew is provided the capabilities to monitor, operate and control the space system to ensure the execution of the mission, prevent a catastrophic event, or prevent an unintentional abort. A mission task analysis determines what crew controls are needed to execute the mission as well as required to help prevent a catastrophic event.

b. Tolerating inadvertent operator action without causing a catastrophic event entails the crew control design to ensure that no critical commands are inadvertently executed. This translates into a requirement for at least two activations for initiating a critical command. One example would be to include separate arm and fire buttons to send a critical command on a panel.

c. The crew must have the capability to manually override higher-level software control and automation. This necessitates that crew controls contain the proper physical controls for the manual override of automation such as automatic docking to another space vehicle.

d. Manual control of the spacecraft must be available to the crew except during atmospheric flight. An additional part of this requirement is Level 1 handling qualities of 1,2, and 3, as defined by the Cooper-Harper Rating Scale [6], during manual control of the spacecraft. For crew control, this means a physical device that permits the crew to manually control the spacecraft. Traditional devices for this application are rotational and translational hand controllers, but as we evaluate more innovative controllers the handling quality implications must be addressed.

The last fundamental principle is tied to crew survival and abort. For crew control, two areas are considered part of meeting this principle-- a launch escape physical control as a backup to automated abort software, and displays to show the status of the hazardous situation. For the most part, crew displays are key to providing situational awareness of an impending launch abort--either from Earth or the Moon.

V. Human-Rating Through NASA Systems Engineering (SE) & Human Systems Integration (HSI) processes

Until now, this paper has focused on describing the human rating principles related to crew control and some of the requirements that come from those principles. Because of the complexity of the human-machine interaction related to crew controls, the preferred approach in developing a crew control human-rated system is the use of Human Systems Integration (HSI) as part of the systems engineering (SE) process. The following sections provide a brief description of these two NASA processes. and a description of how the human rating

of the crew controls occurs through the use of these two processes.

A. NASA Systems Engineering (SE) Process

There are several versions of the systems engineering process used by industry, the Department of Defense (DoD), and NASA. All encompass the methodical way of creating effective solutions to problems and managing the technical complexity of the program/project. Like many industries, the NASA SE process follows a VEE model [7]. Figure 7 shows a representation of the VEE model NASA uses along with the name of the processes.

For NASA, the SE process, as defined in NPR 7123.1 [8], defines three major processes: System design (left side of the VEE), Product Realization (right side of the VEE), and Technical Management (cross-cutting). Though the process looks sequential as a diagram, the SE process is actually iterative.

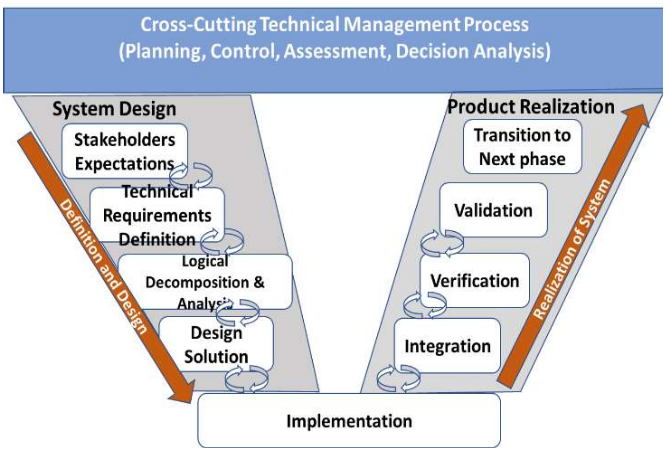

Fig. 7. Systems Engineering VEE Model (Credit Author)

The left side of the NASA SE process is the System Design process that defines the definition/decomposition of the problem/solution. The System Design Process is where most of the system development that will satisfy the problem transpires. Elicitation with the stakeholders and Concept of Operations (CONOPS) begin defining system requirements. Requirements development and analysis, logical decomposition/architecture design, functional analysis/allocation, and technical solution are some of the activities that occur. Also, prototypes and modeling & simulation begin early to flesh out requirement issues or technical maturity challenges. The Design Solutions lead to a preliminary design review and then to a detailed design that is baselined at the critical design review(CDR) milestone. If the design passes the CDR milestone review exit criteria, the program/project gives the go-ahead to begin developing the flight system.

The Integration/Verification/Validation process (or the right side of the VEE model) defines the activities that integrate the system/subsystem components and verifies that it meets the requirements. Formal verification begins after the system/subsystem is integrated. For many of the space systems, such as crew controls, this activity is a continuation of early developmental work during the system design process such as human-centered design discussed in the HSI process section of this paper. A major activity is the qualification and acceptance testing of the subsystem/system as well as the validation test that ensures the crew control was built correctly and, more importantly, the right crew control was developed. Note the iteration arrows in the diagram showing the processes are iterative.

The Technical management process is cross-cutting and provides the SE & HSI activities for planning, assessing, and controlling the implementation of the system design and product realization processes. It also guides technical decision-making (decision analysis). Additionally, requirements management, interface management, configuration control, and risk management are also key technical management areas that ensure the system will meet the requirements.

B. NASA Human Systems Integration (HSI) Process

As defined by the NASA HSI Community of Practice, HSI is a required interdisciplinary integration of the human as an element of a system to ensure that the human and software/hardware components cooperate, coordinate, and communicate effectively to successfully perform a specific function or mission. HSI is a comprehensive technical and management process. It is a technical process to ensure human performance is considered in the design and a management process to guarantee all aspects of the development life cycle consider the human.

Since the days of the Mercury program, NASA has always considered humans in space systems development. Other agencies such as DoD and the railroad sector have recognized the importance of HSI in system development. With the increase in electronic component computing power, complex software development such as artificial intelligence and machine learning, and space missions with increasing complexity, NASA is mandating applying HSI to the SE process in the Artemis campaign [9].

To aid in the application of HSI in NASA programs and projects, a NASA HSI Handbook was developed [10]. The handbook provides general guidance and information to an HSI practitioner on implementing HSI as part of the SE life cycle and describes tailoring HSI to the program. An HSI Plan (HSIP) template is also included. An HSIP is now required as part of the SE process as noted in NPR 7123.1.

HSI goes beyond human factors engineering as it includes all domains that affect human performance. Each organization has its specific HSI domains that are critical to integrating the

human with the hardware and software. Figure 8 shows the six HSI domains. A short description of each domain follows.

- Human Factors Engineering: Design and evaluate the system interfaces and operations for human well-being and optimize for safety, operability, and performance while considering human performance characteristics.
- Safety: Implementation of safety considerations across the full life cycle to reduce hazards and risks to personnel, system, facilities, and mission.
- Maintainability and Supportability: Simplified maintenance and accessibility, reliability, optimized resources, spares, consumables, and logistics given mission constraints.
- Operations: Full life cycle engagement of operational considerations into the design, development, maintenance, and evolution of the system.
- Training: Effective training methods and resources to maximize human retention, proficiency, and effectiveness to accomplish mission tasks successfully.
- Habitability: Ensure system integration with the human through design and continual evaluation of internal/external living and working environments necessary to sustain safety, human and mission performance, and human health.

Not shown is the double integration that occurs as part of the HSI process. One integration occurs within each domain trading off solutions for the human such as the optimum location of the crew controls in a habitat or spacecraft given size and weight constraints.

Fig. 8. NASA HSI Domains (Credit: NASA)

The other integration occurs among all the domains to arrive at a solution that considers the total system safety and effectiveness through a closely coordinated SE and human-centered design.

C. Crew Control Trust through the SE and HSI process

Establishing trust in crew controls occurs when it can be demonstrated that the system, comprised of the hardware/software and human in the intended environment, can perform the interactions and interdependencies that establish with confidence the execution of commands reliably and confidently. Trust also reflects a mental state and confidence in one's predisposition to trust another machine such as a crew control system. Four key elements that contribute to establishing trust are:

- System-level Requirements that capture human-rating and human factors requirements.
- Qualification and acceptance testing that ensures the hardware and software were reliably built to the intended environment.
- The hardware and software design, build, and comprehensive realization process ensure the design is safe and contains adequate performance margins, including mitigating hazardous safety-critical software behavior.
- Strong HSI presence early in the program/project to ensure the human element is not overlooked in the development of the crew controls--especially human factors assessment of the tasks required to accomplish the mission, Human in the loop (HITL) test support, Safety, training, and habitability design.

Figure 9 shows a notional diagram of an overlay of HSI processes over the systems engineering processes working together towards crew control trust. The HSI elements in the diagram are not all-inclusive but show where the HSI emphasis is in the systems engineering life cycle. The following description is related to the human rating and crew control trust. Note that the process for the other pieces of the system that interface with crew controls (such as power and flight computers) are also being developed simultaneously.

System requirement development is a critical step toward crew control trust. The reference mission will dictate what space system requirements are needed. This process occurs during the SE system design process. Based on the reference mission, HSI practitioners work with SE to develop a CONOPS and the system requirements that ensure human rating, along with stakeholder requirements are captured. Requirements from the NASA Technical Standard NASA-STD-3001 are included such as limiting acoustic sound pressure level exposure and lighting levels for various task support. These NASA-STD-3001 requirements provide uniform technical requirements for the design, selection, and application of hardware, software, processes, procedures, practices, and methods for human-rated systems.

From the CONOPS and system requirements, an allocation of requirements to hardware, software, or the human is determined. The task(s) allocated to the crew control are analyzed to determine what actions/control commands must be done by the human to accomplish the task. During requirements development, the verification events are also written for later confirmation that the design meets the requirements.

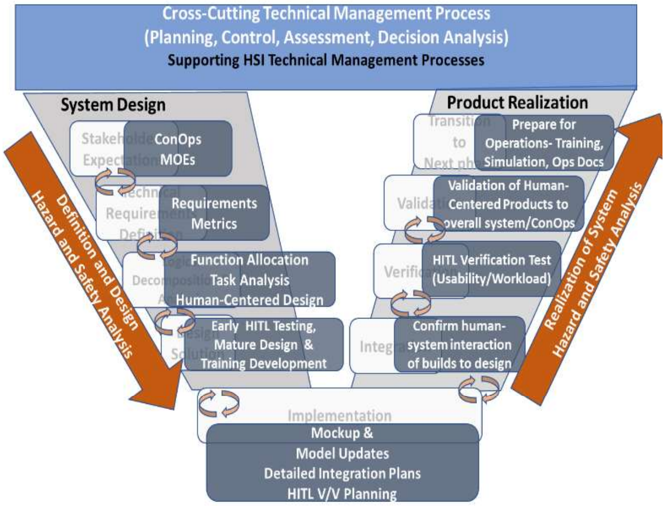

Fig. 9. Notional HSI and Systems Engineering Working Together (Credit: Author)

As the human tasks are defined, the SE/HSI safety subject matter experts perform a human error analysis (HEA). HEA is a systematic approach to evaluating human actions, identifying potential human error, modeling human performance, and qualitatively characterizing how human error affects a system. As defined in the NASA HSI Handbook [10], HEA evaluates human actions and errors to generate system improvements that reduce the frequency of errors and minimize the adverse effects on the system. HEA is performed as part of the system development process. It is a projective approach requiring the analyst to identify, conceive, and predict scenarios where human actions could contribute to a catastrophic outcome.

In addition to HEA, a hazard analysis (HA) is performed to assess potential hazards with crew control commanding. The hazard analysis assesses what may go wrong, the controls to put in place, and the verification of the controls against the hazards. A HA is also performed on the evolving hardware/software design that begins with doing a Failure Modes and Effects Analysis (FMEA) and assessing hardware design margins against the anticipated environment in which the crew controls will be used. A human reliability assessment [11] is also performed to predict potential human errors when interacting with the crew controls. From these analyses, risks are identified. As part of the risk assessment of SE technical management, actions are identified to eliminate, reduce, or track the risk. These activities begin to build trust in the crew control design. Note in Figure 5 that hazard and safety analysis is a continuous ongoing activity throughout the life cycle to ensure safety issues are captured and that any modifications/redesigns do not pose a safety risk.

Models and simulations are used to inform the design in terms of features and performance. Prototypes and developmental engineering models are designed and built for human-in-the-loop (HITL) testing that occurs early and later in the life cycle. Mockups, models, and simulators are updated after critical design review during implementation in preparation for verification activities such as HITL testing. Key modeling and simulation data are critical to maximizing safety. Examples are the simulation response of the hand controllers that manually land the human lander system on the Moon and the manual abort control.

An important part of the HSI/SE process associated with crew controls is the iterative human-centered design (HCD) process that is performed in parallel with the SE process to evolve the human requirements and design, particularly in the early stages of the SE life cycle where changes to requirements and design have minimal cost and schedule impact. HCD begins in the system design process and continues through the product realization phase of the system engineering life cycle. As part of the HCD, crew control usability, human error analysis, situational awareness, and workload analysis are performed to refine the design and formal HITL test procedures. During the HCD process, the HSI domain training begins to formulate crew control training procedures and early HITL testing with the flight-like hardware helps catch design issues overlooked earlier.

Correct requirements and safety features for crew control are of no use unless the hardware and software perform correctly in the intended environment. Consequently, the hardware and software go through a rigorous qualification and acceptance testing campaign to ensure the design can meet requirements. The crew control design is subjected to various environmental testing such as thermal, thermal/vacuum, vibration, and radiation. Acceptance tests typically consist of functional, thermal, and vibration to ensure the system was built with no workmanship errors. Qualification testing stresses the hardware beyond the environmental limits set by the requirements. The software is extensively tested at various build levels. Any software updates require regression tests to ensure there are no unintended side effects of the updates.

Formal verification events (VE) take place as part of the SE product realization process. Verification consists of one or any combination of the methods of test, analysis, inspection, or demonstration to confirm that the crew control system meets each of the requirements. A success criterion is documented for each requirement to use as a basis for accepting the verification results. Once the VE has demonstrated and reported that the requirement has been met, a verification compliance notice is submitted for review for closure.

To summarize, as shown in Figure 10 Venn diagram, establishing trust in crew controls encompasses the reference mission to understand what is needed in terms of system requirements associated with the mission, the human-rating requirements for the mission, the systems engineering process needed, and the human systems integration process to establish trust in the crew controls.

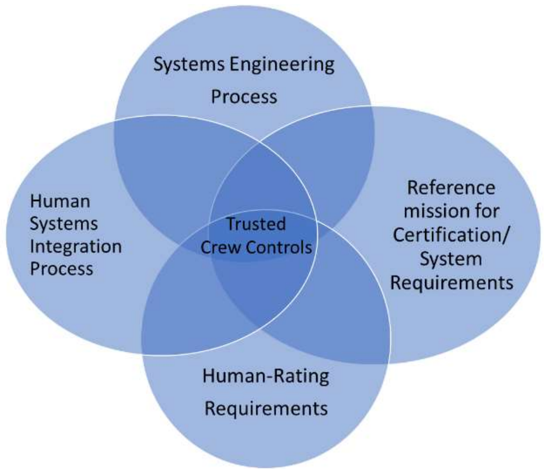

Fig. 10 Venn diagram of all key elements to ensure established trust in the crew controls (Diagram credit: Author).

VI. Conclusion

As human spaceflight missions go deeper into space, the crew will no longer be able to depend on mission control on Earth to help them during safety-critical events. The crew will have to rely on the onboard systems that interface to a crew control panel. This means that the crew control panel system will have to be highly reliable to ensure no safety issues exist in the design that could cause a catastrophic event. This is especially important as the missions extend beyond the Moon and risks/hazards can affect the mental state of the crew. The Artemis missions will provide the opportunity to develop crew control trust in usage during Moon missions and eventually on Mars missions. Establishing trust in the crew controls entails the use of human rating requirements and the use of the SE/HSI processes. Sound engineering design will provide crew control hardware/software margin in the intended environment. The human-centered design will mature the crew control design. Qualification and acceptance testing will provide hardware reliability. Validation testing will provide confidence in the software behavior. Finally, the safety process will track risks and mitigate them, ensuring the crew controls can be trusted when used in the mission.

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